INFLATABLE/RIGIDIZABLE STRUCTURES FOR SPACE APPLICATIONS

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BACKGROUND

- Launch cost is a major part of the life cycle cost of a space flight mission.
- Payload mass and volume are two of the most important drivers of launch cost.
- Technologies that can reduce launch mass and volume are continuously being pursued.
- Space inflatable structures technology can potentially offer order-of-magnitude reductions in mass and launch volume of future space flight systems.

COMPARISON OF LAUNCH SYSTEMS

Launch Systems	Mass (kg) to SSO (200/1000 km)	Dyn. Envelop of Std. P/L Fairing, D x L (m)	Approximate Cost ($M)**
STS	24,635*	4.57 x 18.29	N/A
Titan IV (B-NUS)	16,500/900	4.57 x 10.92	250 - 300
Ariane 4 (4L)	7,500/5,400	3.65 x 5.98	≅ 120
Atlas (II AS)	7,050/5,660	2.92 x 4.47	105 - 145
Delta (II 2024)	2,400/1,890	2.74 x 4.93	50 - 60
Athena (II)	1,280/960	1.98 x 2.64	30 - 35
Taurus (2110)	1,020/650	1.37 x 2.79	30 - 40
Pegasus (XL)	320/150	1.17 x 1.21	≅ 20

* LEO only, need the addition of an upper stage to reach higher orbits.

** Used to compare the range of costs.

INTRODUCTION

- Large space structural systems (e.g., solar arrays, telescope reflectors, sunshields, solar concentrators, radar antennas, etc.) must be compactly packaged for launch and then deployed in space.
  - Traditional way: Use electromechanical devices
  - New way: Use inflation pressure

INTRODUCTION (Cont'd)

- A space inflatable structure is typically consists of one or more tubular elements - booms or tubes - that are made of membrane or fabric materials.
- When not pressurized, these booms/tubes can be folded up or rolled up and stowed in a very small volume for launch.
- In space, the booms/tubes are pressurized by cold gas and deployed to achieve their design configurations.
- Structural stiffness is derived from tensioning of the walls of the deployed booms/tubes.

ADVANTAGES OF INFLATABLE STRUCTURES

In addition to ultra-lightweight and excellent packaging efficiency, space inflatable structures also have the following advantages over its mechanically deployed counterparts:

- Simpler design (10's of parts vs. 100's of parts)
- Higher deployment reliability
- Lower recurring (materials and fabrication, etc.) cost

HISTORY

- An inflatable reflector concept for radar applications was first proposed and demonstrated by Goodyear in the late 1950's.
- NASA studied space inflatable structures in the early 1960's and applied this technology to its NASA's ECHO balloon missions.
- Interest in space inflatables was re-generated when the Inflatable Antenna Experiment (IAE) mission was flown by NASA on a Spartan free flyer launched from the Space Shuttle in May 1996.

THE IAE SPACE DEMOSTRATION

- The IAE is an inflatable off-axis parabolic reflector with:
  - 14-meter canopy aperture of less than 2 mm RMS configuration error
  - The canopy is made of 0.25-mil Mylar film, one surface is metalized and the other is transparent
  - Support structure consists of a torus and three 28-meter struts, both of which are made of urethane-coated Kevlar membrane
  - Total weight is about 60 kg.
- The IAE demonstrated that a large inflatable reflector can be compactly stowed for launch and deployed by inflation pressure in space.

TECHNICAL CHALLENGES

Post-flight reviews of the IAE indicated that many technical challenges remain to be addressed, including:

1) Control and stability of deployment
2) Modeling and analysis tools
3)* Materials characterization and long-term space survivability
4)* Processing and handling of ultra-thin films
5)* Space rigidization
6) Ground test methodology

* Materials-related.

MATERIAL PROPERTIES

- Polymer films, woven fabrics, resins, adhesives, and coatings are used to fabricate space inflatable structures.
- Current development relies on off-the-shelf commercial products (e.g., Mylar, Kapton, and woven Nylon, Kevlar, and graphite fabrics).
- Costly to obtain reliable data on mechanical, thermal, and optical properties, such as:
  - Strengths, modulus, density
  - CTE, solar absorptance/emissivity, thermal/electrical conductivity
  - Optical reflectivity and transparency
  - Outgassing, toxicity, stress corrosion cracking
  - Effect of space environment on properties mentioned above

SPACE SURVIVABILITY

- Space missions require inflatable structures that can survive in specific space environments for a long period (> 10 years).
- For commercially available and state-of-the-art polymers, the effects of space environment are not yet adequately known and controlled tests are needed to determine these effects.
- Polymeric materials will degrade by exposure to thermal cycling, UV radiation, electrons, protons, AO in LEO, micro-meteoroid impacts, and space charges that may result from travel through plasma.
- Polymers of long-term space survivability may need to be developed.

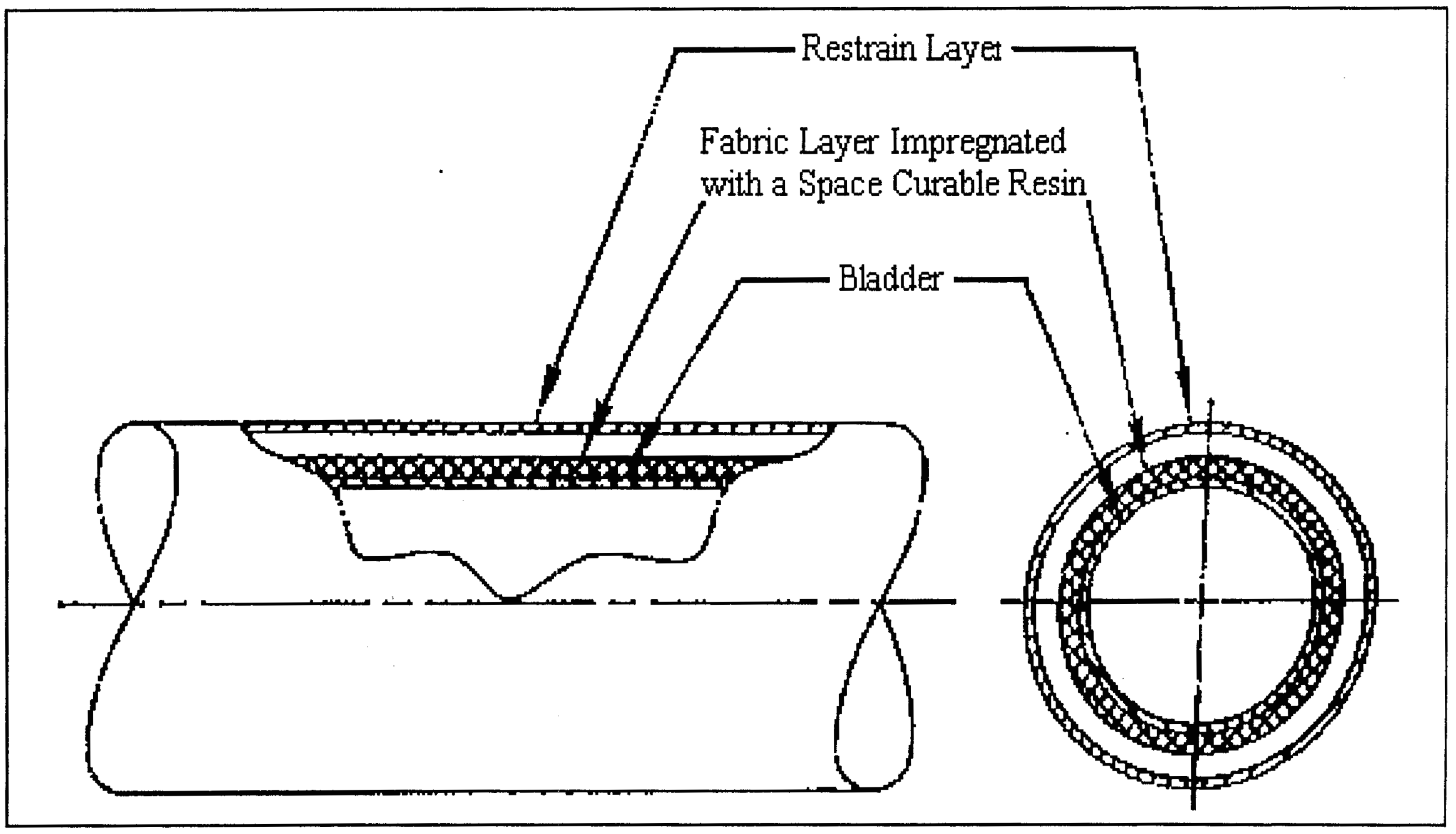
PROCESSING & HANDLING OF THIN FILMS

- Many space inflatable systems (e.g., solar arrays, solar sails, and sun shades) involve the use of large membrane apertures that are made of thin films.
- Interstellar missions will require solar sails of apertures as large as 10^6 m^2. The film thickness needs to be as low as 1 μm and the areal density in the range of 1 gram/m^2.
- Processing and handling of large, ultra-thin membranes need to address many practical issues, including:
  - Seaming
  - Tensioning
  - Coating
  - Packaging
  - Management of membranes during deployment
  - Long-term storage in the "packaged" condition

SPACE RIGIDIZATION

- Leakage of inflatable structures will occur due to impacts of micro-meteoroids and space debris - a major concern for long-term missions.
- Rigidization of inflatable structures after deployment eliminate the need of make-up gas.

SPACE INFLATABLE/RIGIDIZABLE STRUCTURES



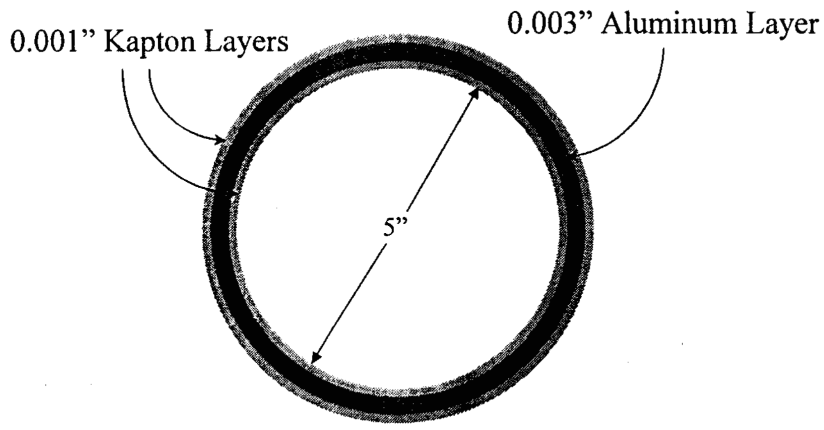
Typical Construction of Space Inflatable/Rigidizable Booms

SPACE RIGIDIZATION METHODS

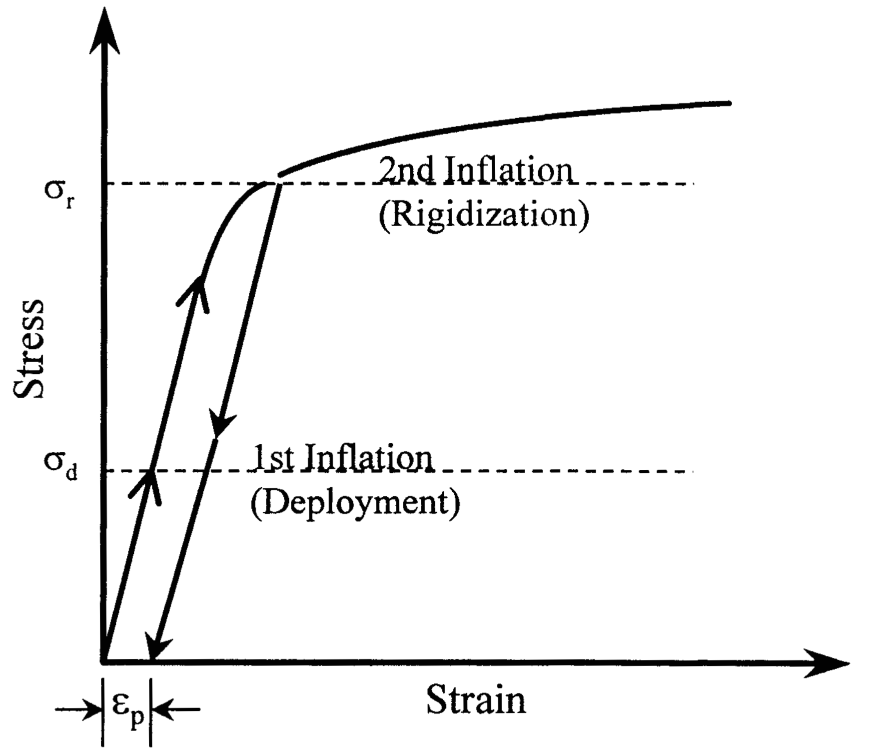
- For most space inflatable/rigidizable booms, the basic construction consists of three membrane layers:
  - The inner layer (bladder), made of a thin polyimide film, serves as a pressure barrier
  - The middle layer, made of woven fabric materials (Nylon, Kevlar, graphite, etc.), is impregnated with space curable resins, including hydro-gel, thermoset, thermoplastic, UV-curable.
  - The outer layer, also made of thin film, is used to constrain the resin before it is cured in space.
- Curable foams and shape-memory materials are also being studied for space rigidization of inflatable structures.

A DESIRABLE SPACE RIGIDIZATION METHOD

- Requires no or low space power
- Produces no or low in-orbit outgassing/contamination
- Has minimum impact to system mass
- Is adaptive to high-efficiency packaging for launch
- Has long shelf life in ambient
- Is suitable for ground testing and verification (reversibility)



Aluminum Laminate Boom



Rigidization By Using
Stretched Aluminum Laminates

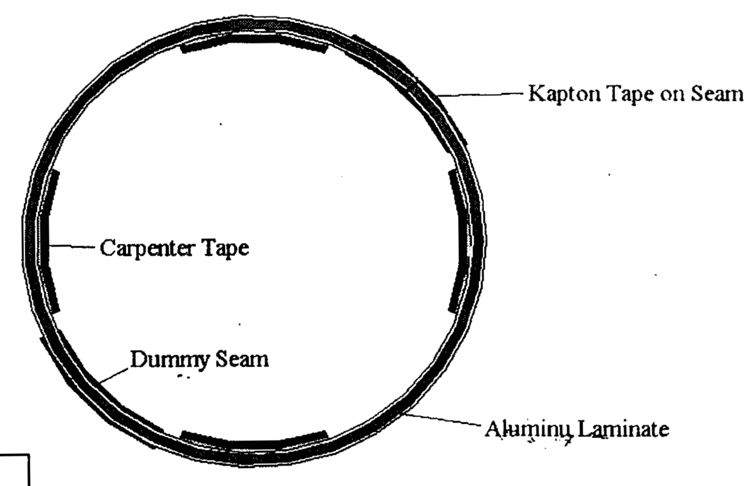
STRETCHED ALUMINUM LAMINATE

- Advantages:
  - Uses the same pressure inflation system already needed for inflation deployment of the structure
  - Does not require space power
  - Has negligible level of outgassing/contamination
  - Aluminum and Kapton have long space heritage
- Disadvantages:
  - Only very thin layer of aluminum (< 0.004”) can be used
  - Poor structural load-carrying (buckling) capability
  - Failure usually caused by local crippling - hard to control or predict

Spring-Tape Reinforced (STR) Aluminum Laminate Booms

Materials and Construction:

- Aluminum Laminate Tube:
  - One 3-mil aluminum layer
  - Two 1-mil Kapton constraining sheets
- Reinforced by four 1-in-wide spring steel tapes in the longitudinal direction
- Diameter - 3 inches



Weight:
- **Tube - 0.18 kg/m**
- **End Caps - 0.7 kg**

Total weight of a 5-m boom = 1.5 kg

Reference: Lou, M.C., Fang, H., and Hsia, L., "Development of Space Inflatable/Rigidizable STR Aluminum Laminate Booms," Presented at the AIAA 2000 Aerospace Conference, September 2000, Long Beach, CA.

Axial Buckling Load Tests

Test Set-Up

Buckling Load Test Results

Tube number	Buckling load
1	118.0 (lbs)
2	114.0 (lbs)
3	135.2 (lbs)
4	149.6 (lbs)
5	134.4 (lbs)
6	136.4 (lbs)
7	165.2 (lbs)

The test boundary is pin-pin.
If the boundary condition is changed to pin-clamped, buckling load would be doubled.

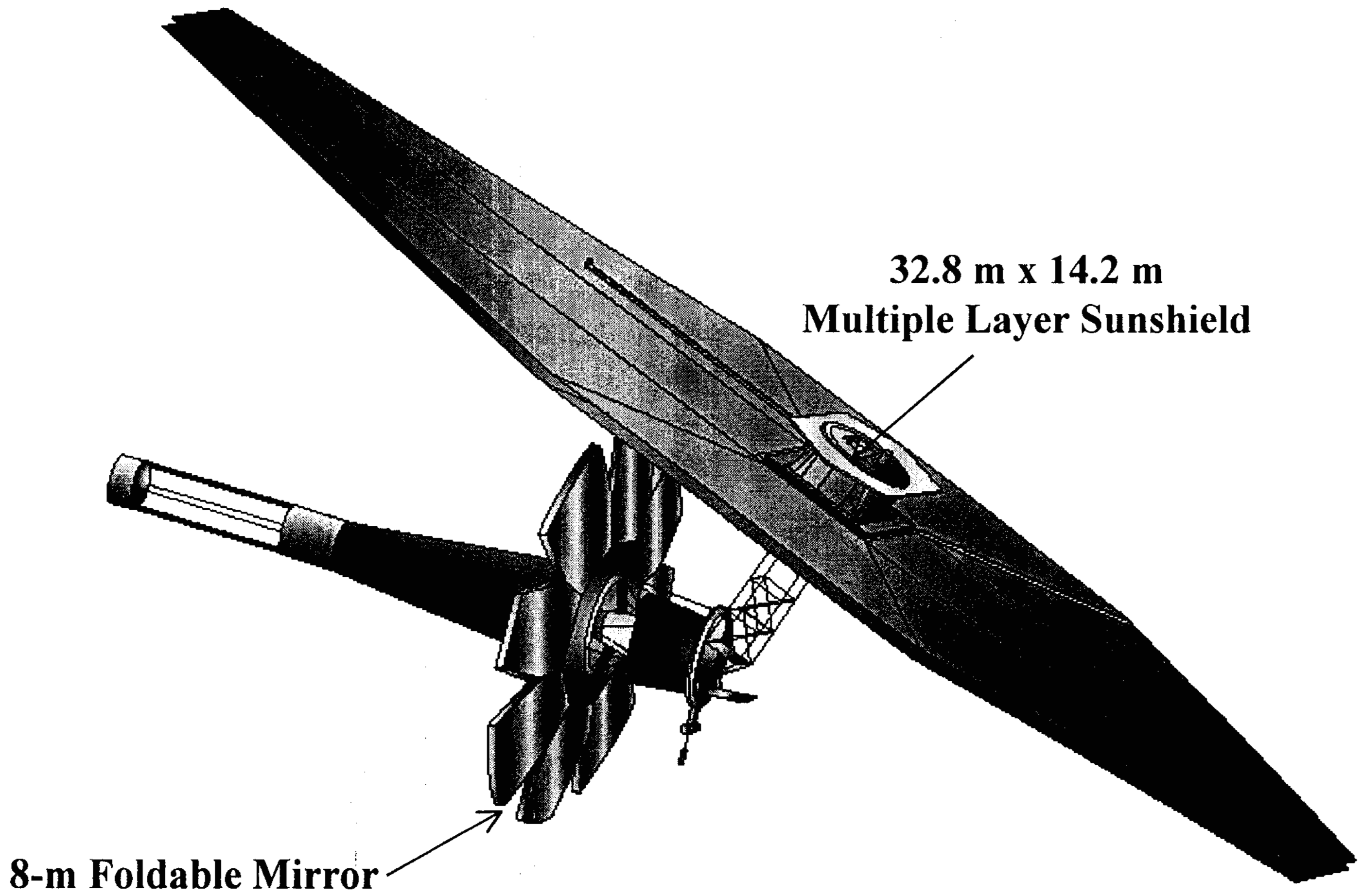
EXAMPLE APPLICATIONS

1) Inflatable Sunshield for the Next Generation Space Telescope (NGST)

2) Inflatable Synthetic-Aperture Radar (SAR) Array Antenna

NGST INFLATABLE SUNSHIELD

- Next Generation Space Telescope (NGST) is being developed as a replacement of the Hubble Space Telescope.
- NGST requires a 32.8 m x 14.2 m sunshield to passively cool the near-IR telescope to an operating temperature of < 60 K.
- Requirements of NGST sunshield include:
  - Ultra lightweight
  - High packaging efficiency
  - High deployment reliability
  - 5 -10 years of mission life at L2
- A sunshield consisting of inflatable structures and multiple layers of thin thermal films is considered.

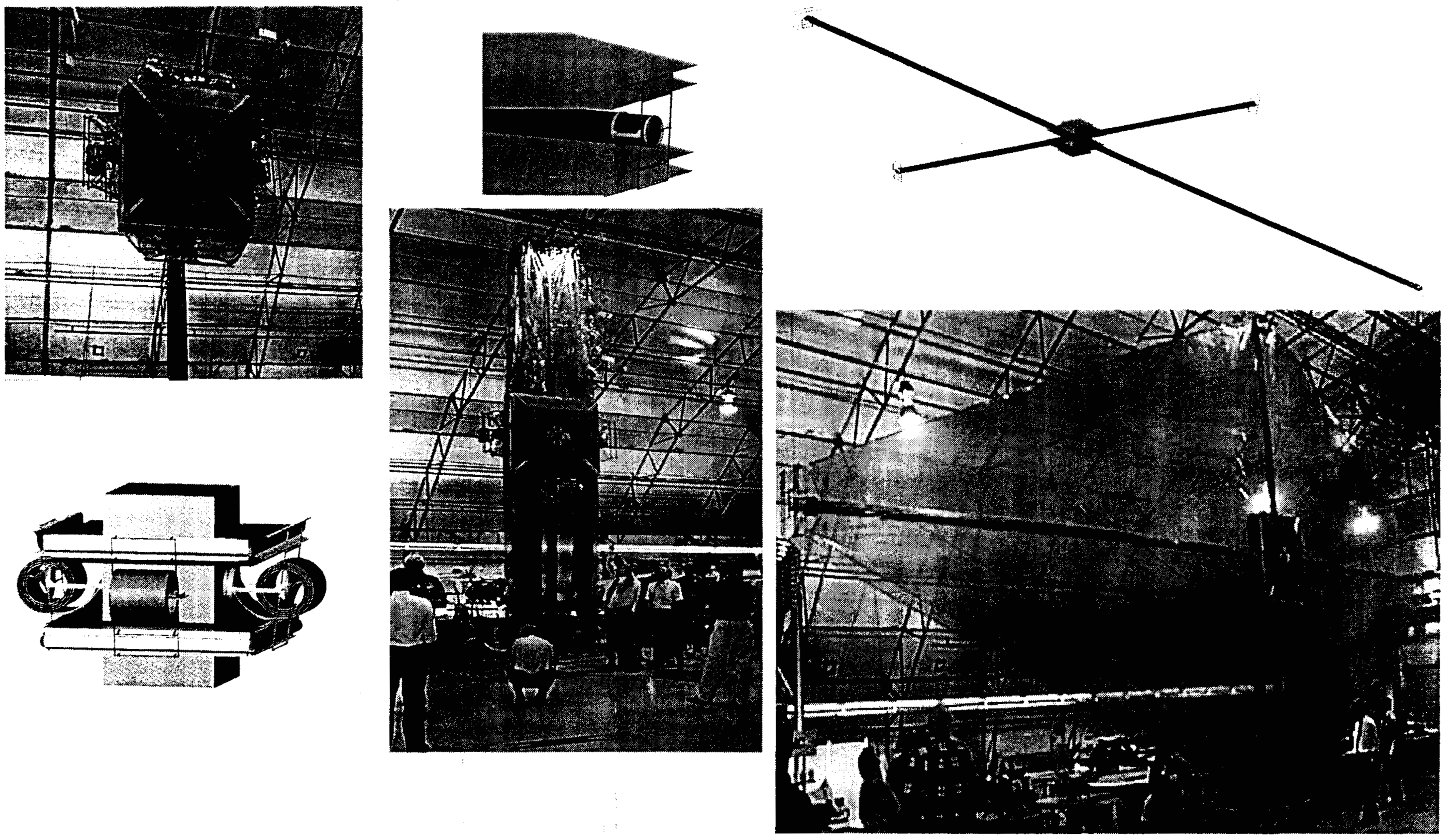


The NGST Reference Architecture

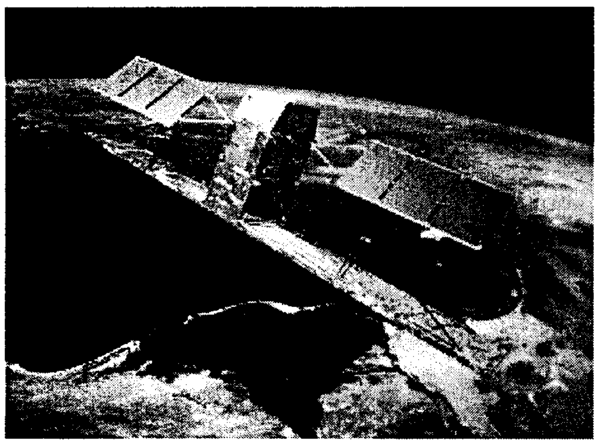
NGST INFLATABLE SUNSHIELD (Cont'd)

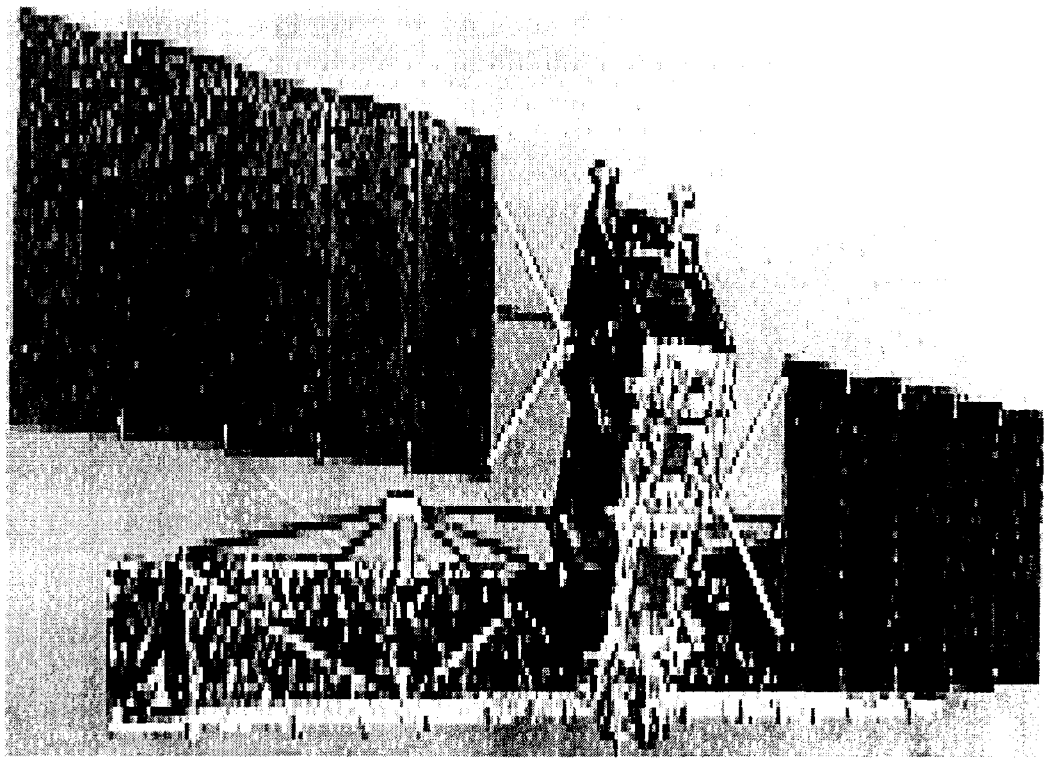
- An inflatable NGST sunshield has many advantages over its mechanically deployed counterpart:
  - 20 - 30% lighter
  - 60 - 80% smaller launch volume
  - Cheaper - $5^-M vs. $10^+M
- A major concern is controllability of inflation deployment.
- A 1/2-scale engineering model was developed in 1998 to test-verify controlled deployment and rigidization.
- NASA was working on an space experiment (called the Inflatable Sunshield In Space or ISIS) in 1999 and 2000. However, this effort was terminated last year due mainly to lack of Shuttle flight opportunity.

SPACE INFLATABLE/RIGIDIZABLE STRUCTURES



NGST Inflatable Sunshield EM Deployment Test





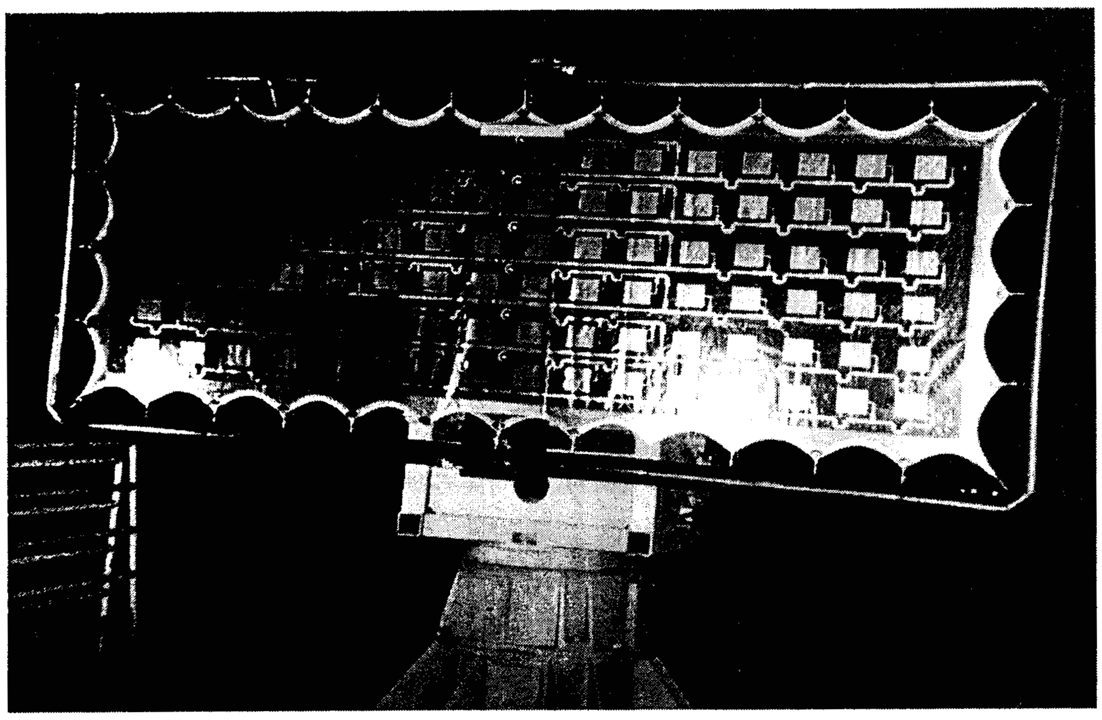
SAR Antenna of Traditional (Rigid-Panel) Design

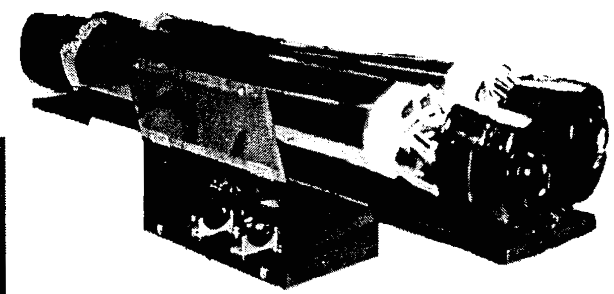
INFLATABLE SAR

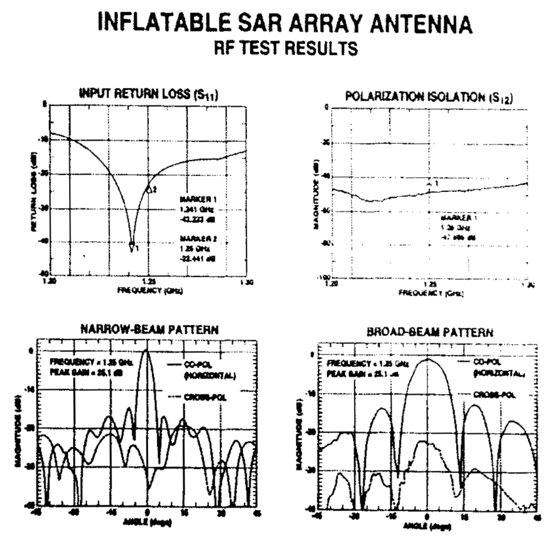
- More synthetic-aperture radar (SAR) missions are needed to assess resources and monitor changes of the Earth - rigid antennas are too big and too heavy.
- JPL was tasked by NASA in 1996 to develop an advanced ultra-lightweight SAR array antenna with RF requirements:
  - 10 m x 3 m aperture
  - L-Band (1.25 GHz operating frequency)
  - Dual polarization and 80 MHz bandwidth
- Radar array is formed by three thin-film membrane layers:
  - Top layer is the radiating plane
  - Middle layer is the ground plane
  - Bottom layer is the micro-strip transmission line plane.

INFLATABLE SAR (Cont'd)

- Mechanical Requirements:
  - Lightweight (less than 3 kg/m^2 of system mass
  - Small launch volume (targeted for launch by Taurus or Athena)
  - Flatness of tensioned membrane layers to be 1 cm RMS
  - Separations to be 1.27 cm between the top two layers and 0.63 cm between the bottom two layers (both with $\pm$ 10% tolerances).
- Two RF-functional 1/3-scale EMs were built and tested.
  - EM by ILC-Dover: Urethane-coated Kevlar booms
  - EM by L'Garde: Stretched aluminum laminate booms
- As a precursor to the inflatable SAR flight experiment (ISAR), a full-scale, single-wing engineering model is being developed at JPL for mechanical testing.







RF Test of An Inflatable SAR (ISAR) EM

Long-Range

Technology Development Roadmaps

Space Inflatable/Rigidizable Structures

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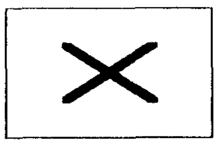
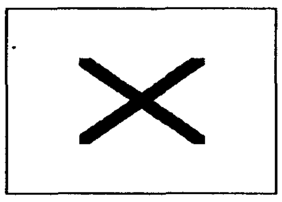


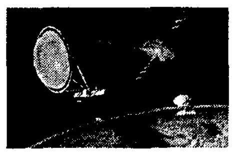
Inflatable Structures

- Tubular structural elements
- Inflation deployment control
- Specialized design and analysis tools
- Materials selection and characterization
- Experimental rigidization technologies
- Scaling laws and ground test methodologies

Enables ground tests, space demos, and technology validation in space

- Inflatable SAR Demo.
- Inflatable Reflectarrays
- ISIS , ISAE, etc.



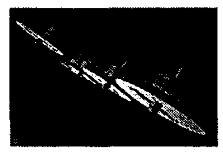


Space Rigidization & Survivability

- Long-term (> 3years) space survivability
- Space-validated rigidization methods
- Space-durable structural materials and thin-films
- Lightweight, compact inflation systems
- Hi-precision fabrication and assembly
- Space-validated design, analysis and performance simulation capabilities

Enables planar inflatable structures* of up to 100 m and reflectors with D/ε ratios of up to 10^5**

- GeoStorm Warning
- NGST, ARISE
- Lightweight, low-cost SAR Missions
- S/A for ESS Missions

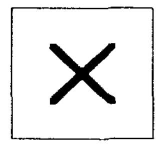


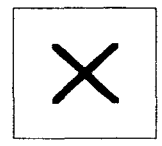
Hi-Precision Structures for Extreme Space Environments

- Survivability in extreme space environments
- Ultra-hi-precision (sub-μm) fabrication and assembly
- Advanced space rigidization concepts
- Adaptive structures and thin-film optics
- In-orbit configuration correction and pointing adjustment

Enables large space optics & reflectors with D/ε ratios of up to 10^7

- TPF
- Large Aperture Observatories
- Exo-Planet Imaging Missions





Space Adaptation & Assembly

- In-orbit configuration change and expansion
- Self-monitoring
- Self-reparability
- Space-based fabrication & assembly

Enables adaptive and expandable space structural systems

- Interstellar Missions
- Evolving Space Colonies

* For examples, solar arrays, sun shades, and solar sails
** D = Aperture diameter; ε = RMS surface error

2001 **2007** **2015** **2025**

M.C.Lou; Jan. 2000

Large Apertures (Reflectors and Concentrators)

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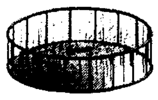
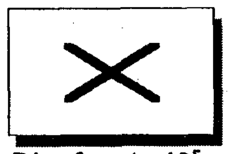



D/ε of up to 10^4

- Support structure: inflatable torus or deployable FRP truss
- Reflective surface: thin-film lenticular or wire mesh dish
- Analysis capability for predicting in-orbit configuration accuracy
- Improvements in fabrication and assembly
- Hi-efficiency packaging concepts

Enables reflectors and concentrators with diameters of up to 20 m and a few mm RMS configuration errors

- RF Reflectors
- Technology Validation in Space

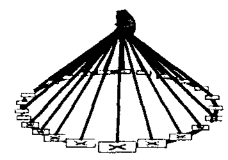


D/ε of up to 10^5

- Long-term space survivability
- Space rigidizable torus and support struts
- Thin-film lenticular or hybrid reflective surface (e.g., a thin-film aperture supported by wire mesh)
- Space-durable thin films
- Space-validated design and predictive capabilities
- Hi-precision fabrication, assembly and ground testing

Enables reflectors and concentrators with aperture diameters of up to 40 m and/or sub-mm RMS configuration errors

- ARISE
- Sub-mm Astronomy
- Space Solar Power
- Solar Propulsion

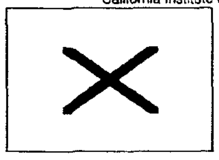


D/ε of up to 10^7

- Actively controlled support structure
- In-space aperture precision adjustment
- Adaptive thin-film optics
- Ultra-hi-precision fabrication and assembly
- Innovative ground test methods and measurements

Enables large apertures with diameters of up to 100 m and/or micro-level RMS configuration errors

- TPF
- IR Telescopes
- Optical Communication
- Earth Science: Event Monitors
- Exo Planet Missions



D/ε ratio of up to 10^9

- Break-through systems concepts
- Breakthrough design, fabrication, assembly and test methodologies

Enables very large apertures with diameters of up to 1,000 m and/or sub-micron RMS configuration errors

- Deep-Field Imaging Observatories

2001	2007	2015	2025

* D/ε is the ratio of aperture diameter divided by RMS surface error

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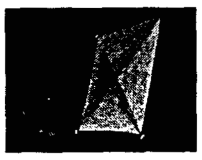
Large Lightweight Space Structures
Solar Sails

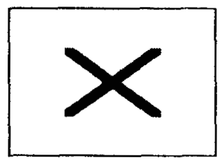


40 to 70 m, 20 g/m²

- Space deployable booms of up to 40 m long (inflatable or FRP)
- Controlled deployment
- Analysis capability for zero-g deployment and performance simulations
- Off-the-shelf or experimental thin films (8 to 16 μm thick)
- Optical reflective coatings
- Hi-efficiency packaging

Enables ground tests and space demo. & technology validation in space

- Solar Sail Space Demo.
- ST-5

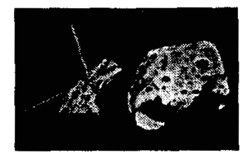


100 m, 10 g/m²

- Space rigidizable booms or radial thin-ribbon ribs
- Spin-deployment and stabilization
- Structure-control interactions
- Space-durable thin-film sails (3 to 5 μm thick) or super-lightweight composite sails
- Scaling laws for ground testing of scaled models

Enables non-Keplerian orbits

- GeoStorm Warning
- Mercury Orbiter

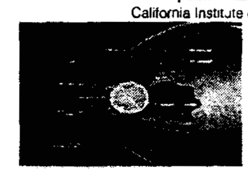


200 m, 3 to 5 g/m²

- Survivability in extreme space environments
- 5 to 10 years mission life
- Spin-deployment and stabilization
- Ultra-thin, ultra-light thin-film (0.5 to 1 μm thick)
- Ultra-thin reflective coatings
- Advanced design and simulation tools
- Advanced fabrication and assembly

Enables long-term low-thrust interplanetary propulsion

- Comet Nucleus Sample Return
- Neptune Orbiter
- Titan Explorer
- Saturn Ring Observer
- Halo Orbit Missions



800 m, 1 g/m²

- Long (> 10 years) mission life
- Innovative system configurations
- Innovative sail concepts
- New structural and sail materials
- In-space fabrication and assembly

Enables 250 AU space travel in 10 years

- Outer Planet Missions
- Interstellar Missions

2003 **2005** **2007** **2015**

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JPL
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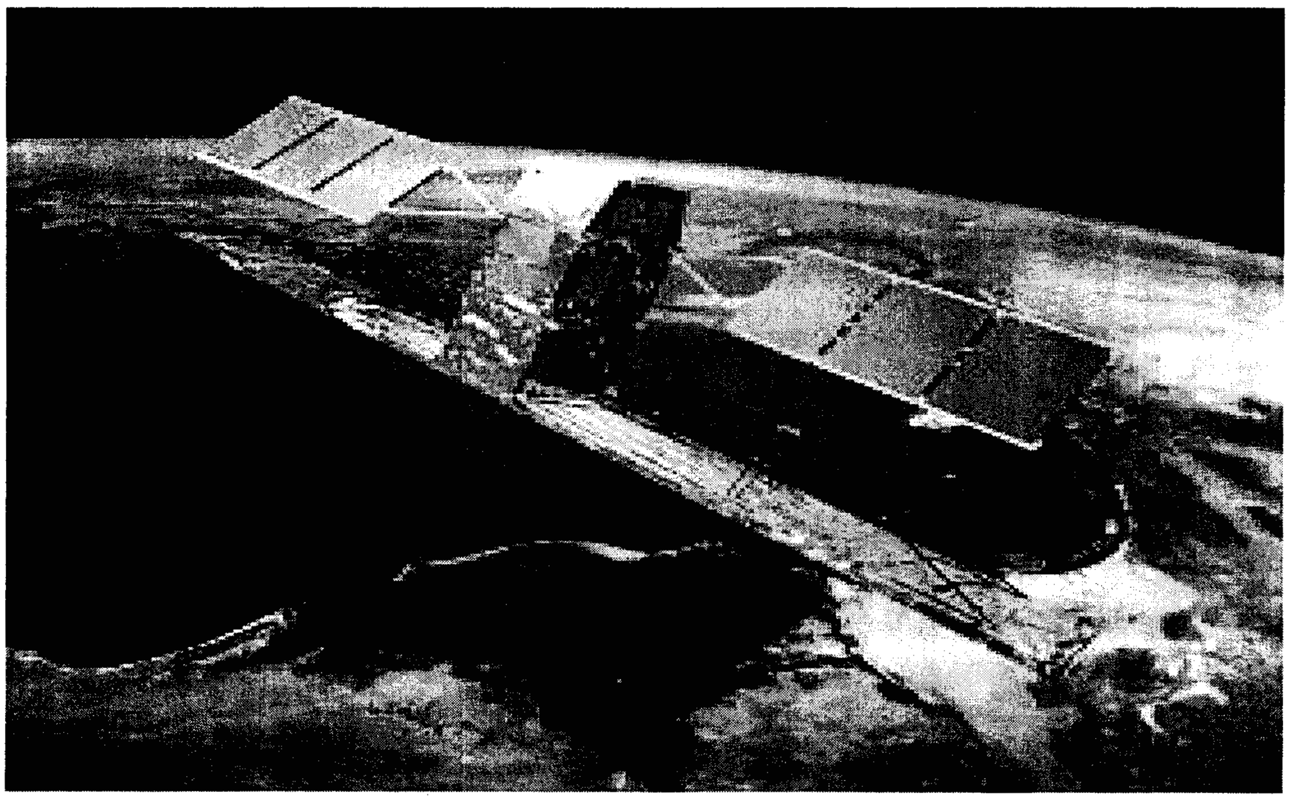

DEPLOYMENT CONTROL

- Uncontrolled inflation deployment of long flexible tubes can be highly volatile and may damage flight hardware and cause catastrophic mission failures.
- Various inflation deployment control concepts have been developed, including:
  - Sequentially deployed compartments/sections
  - Embedded constant-Force coil springs
  - Velcro Strips
- Stable deployment can be achieved by providing resistive forces to balance the inflation pressure -- this has led to the invention of other advanced control approaches.

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- Structural stiffness is derived from tensioning of the walls of the deployed booms/tubes.

ADVANTAGES OF INFLATABLE STRUCTURES

In addition to ultra-lightweight and excellent packaging efficiency, space inflatable structures also have the following advantages over its mechanically deployed counterparts:

- Simpler design (10's of parts vs. 100's of parts)
- Higher deployment reliability
- Lower recurring (materials and fabrication, etc.) cost

JPL
Jet Propulsion Laboratory
California Institute of Technology

HISTORY

- An inflatable reflector concept for radar applications was first proposed and demonstrated by Goodyear in the late 1950's.
- NASA studied space inflatable structures in the early 1960's and applied this technology to its NASA's ECHO balloon missions.
- Interest in space inflatables was re-generated when the Inflatable Antenna Experiment (IAE) mission was flown by NASA on a Spartan free flyer launched from the Space Shuttle in May 1996.

THE IAE SPACE DEMOSTRATION

- The IAE is an inflatable off-axis parabolic reflector with:
  - 14-meter canopy aperture of less than 2 mm RMS configuration error
  - The canopy is made of 0.25-mil Mylar film, one surface is metalized and the other is transparent
  - Support structure consists of a torus and three 28-meter struts, both of which are made of urethane-coated Kevlar membrane
  - Total weight is about 60 kg.
- The IAE demonstrated that a large inflatable reflector can be compactly stowed for launch and deployed by inflation pressure in space.

TECHNICAL CHALLENGES

Post-flight reviews of the IAE indicated that many technical challenges remain to be addressed, including:

1) Control and stability of deployment
2) Modeling and analysis tools
3)* Materials characterization and long-term space survivability
4)* Processing and handling of ultra-thin films
5)* Space rigidization
6) Ground test methodology

* Materials-related.

MATERIAL PROPERTIES

- Polymer films, woven fabrics, resins, adhesives, and coatings are used to fabricate space inflatable structures.
- Current development relies on off-the-shelf commercial products (e.g., Mylar, Kapton, and woven Nylon, Kevlar, and graphite fabrics).
- Costly to obtain reliable data on mechanical, thermal, and optical properties, such as:
  - Strengths, modulus, density
  - CTE, solar absorptance/emissivity, thermal/electrical conductivity
  - Optical reflectivity and transparency
  - Outgassing, toxicity, stress corrosion cracking
  - Effect of space environment on properties mentioned above

SPACE SURVIVABILITY

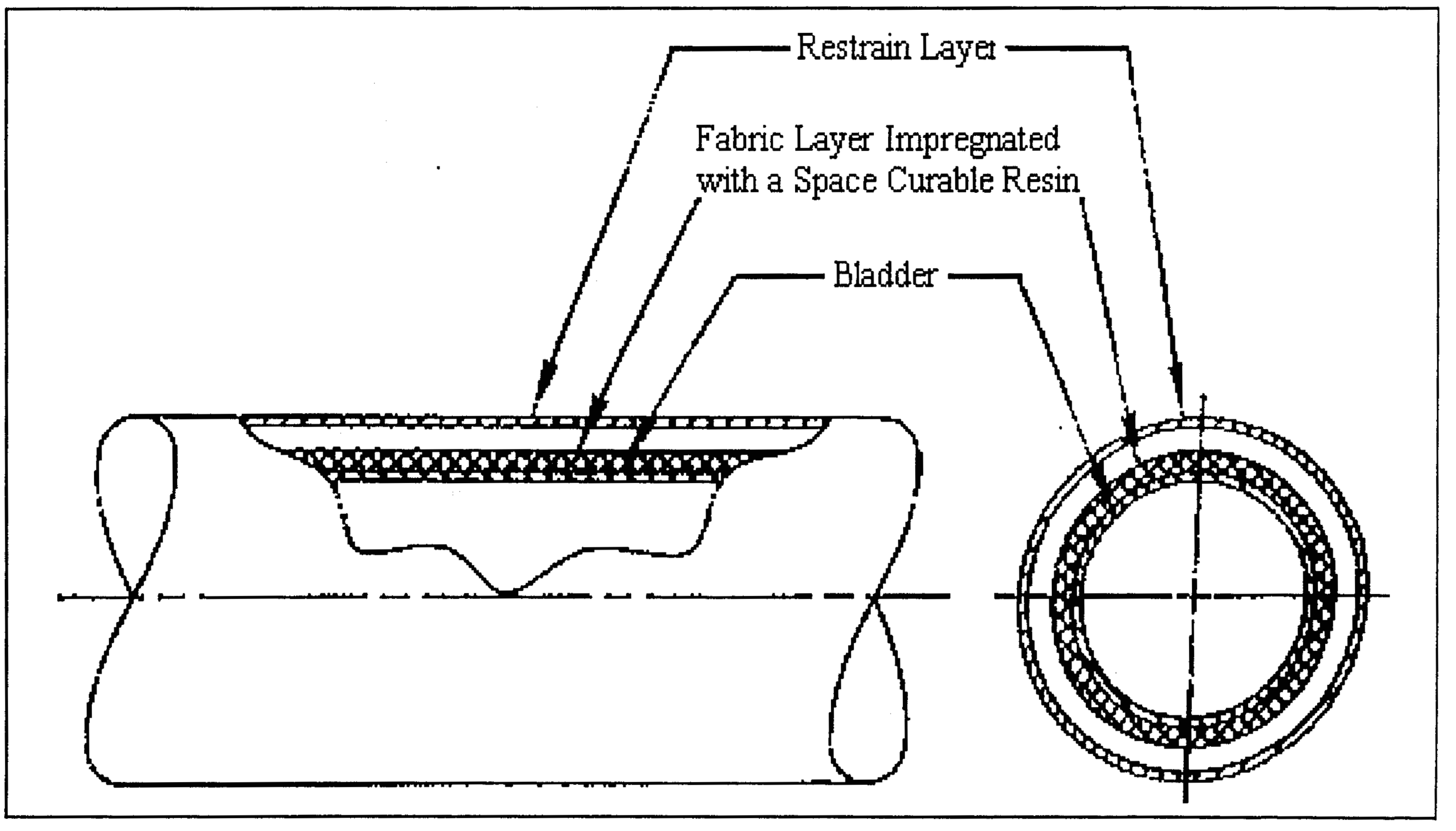
- Space missions require inflatable structures that can survive in specific space environments for a long period (> 10 years).
- For commercially available and state-of-the-art polymers, the effects of space environment are not yet adequately known and controlled tests are needed to determine these effects.
- Polymeric materials will degrade by exposure to thermal cycling, UV radiation, electrons, protons, AO in LEO, micro-meteoroid impacts, and space charges that may result from travel through plasma.
- Polymers of long-term space survivability may need to be developed.

PROCESSING & HANDLING OF THIN FILMS

- Many space inflatable systems (e.g., solar arrays, solar sails, and sun shades) involve the use of large membrane apertures that are made of thin films.
- Interstellar missions will require solar sails of apertures as large as 10^6 m^2. The film thickness needs to be as low as 1 μm and the areal density in the range of 1 $gram/m^2$.
- Processing and handling of large, ultra-thin membranes need to address many practical issues, including:
  - Seaming
  - Tensioning
  - Coating
  - Packaging
  - Management of membranes during deployment
  - Long-term storage in the "packaged" condition

SPACE RIGIDIZATION

- Leakage of inflatable structures will occur due to impacts of micro-meteoroids and space debris - a major concern for long-term missions.
- Rigidization of inflatable structures after deployment eliminate the need of make-up gas.



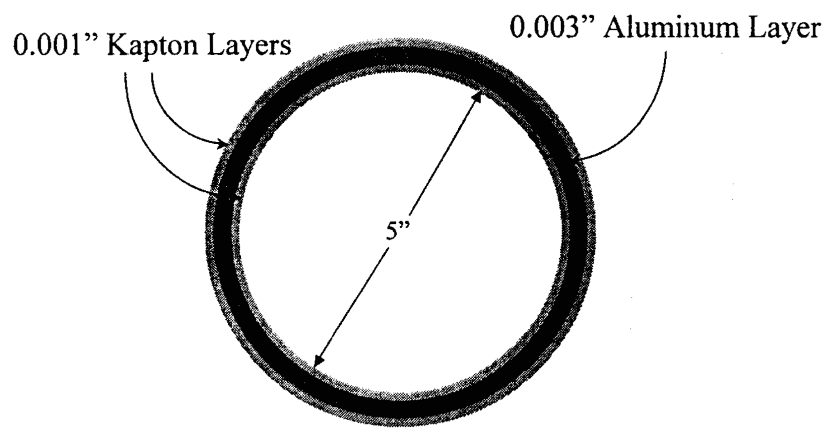
Typical Construction of Space Inflatable/Rigidizable Booms

SPACE RIGIDIZATION METHODS

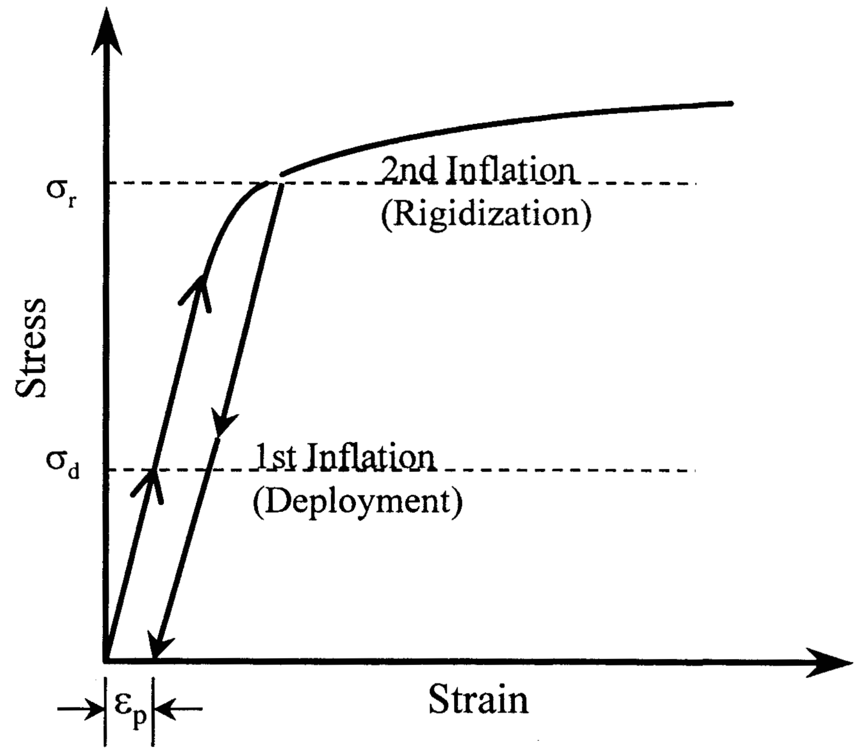
- For most space inflatable/rigidizable booms, the basic construction consists of three membrane layers:
  - The inner layer (bladder), made of a thin polyimide film, serves as a pressure barrier
  - The middle layer, made of woven fabric materials (Nylon, Kevlar, graphite, etc.), is impregnated with space curable resins, including hydro-gel, thermoset, thermoplastic, UV-curable.
  - The outer layer, also made of thin film, is used to constrain the resin before it is cured in space.
- Curable foams and shape-memory materials are also being studied for space rigidization of inflatable structures.

A DESIRABLE SPACE RIGIDIZATION METHOD

- Requires no or low space power
- Produces no or low in-orbit outgassing/contamination
- Has minimum impact to system mass
- Is adaptive to high-efficiency packaging for launch
- Has long shelf life in ambient
- Is suitable for ground testing and verification (reversibility)



Aluminum Laminate Boom



Rigidization By Using Stretched Aluminum Laminates

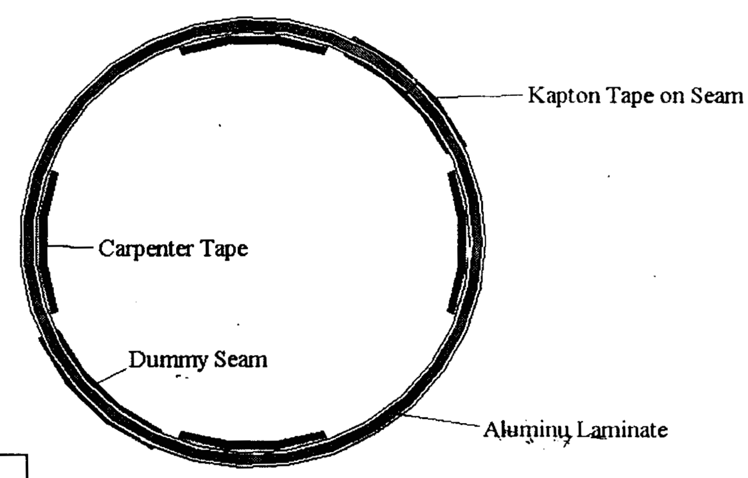
STRETCHED ALUMINUM LAMINATE

- Advantages:
  - Uses the same pressure inflation system already needed for inflation deployment of the structure
  - Does not require space power
  - Has negligible level of outgassing/contamination
  - Aluminum and Kapton have long space heritage
- Disadvantages:
  - Only very thin layer of aluminum (< 0.004”) can be used
  - Poor structural load-carrying (buckling) capability
  - Failure usually caused by local crippling - hard to control or predict

Spring-Tape Reinforced (STR) Aluminum Laminate Booms

Materials and Construction:

- Aluminum Laminate Tube:
  - One 3-mil aluminum layer
  - Two 1-mil Kapton constraining sheets
- Reinforced by four 1-in-wide spring steel tapes in the longitudinal direction
- Diameter - 3 inches

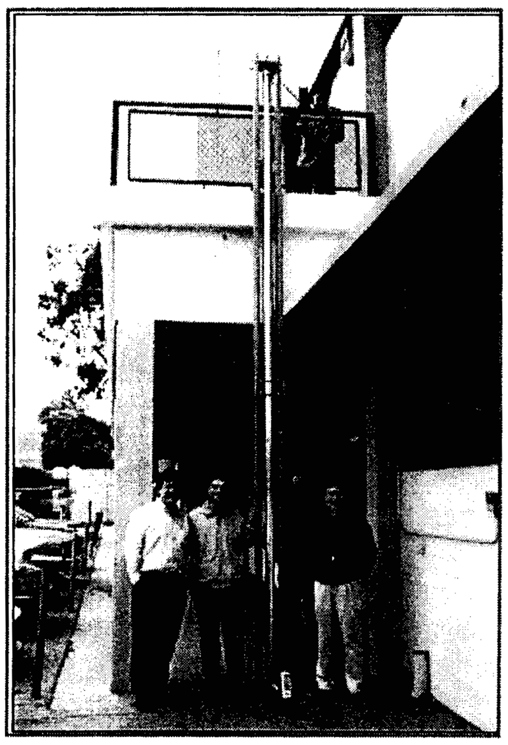


Weight:
- **Tube - 0.18 kg/m**
- **End Caps - 0.7 kg**

Total weight of a 5-m boom = 1.5 kg

Reference: Lou, M.C., Fang, H., and Hsia, L., "Development of Space Inflatable/Rigidizable STR Aluminum Laminate Booms," Presented at the AIAA 2000 Aerospace Conference, September 2000, Long Beach, CA.

Axial Buckling Load Tests



Test Set-Up

Buckling Load Test Results

Tube number	Buckling load
1	118.0 (lbs)
2	114.0 (lbs)
3	135.2 (lbs)
4	149.6 (lbs)
5	134.4 (lbs)
6	136.4 (lbs)
7	165.2 (lbs)

The test boundary is pin-pin.
If the boundary condition is changed to pin-clamped, buckling load would be doubled.

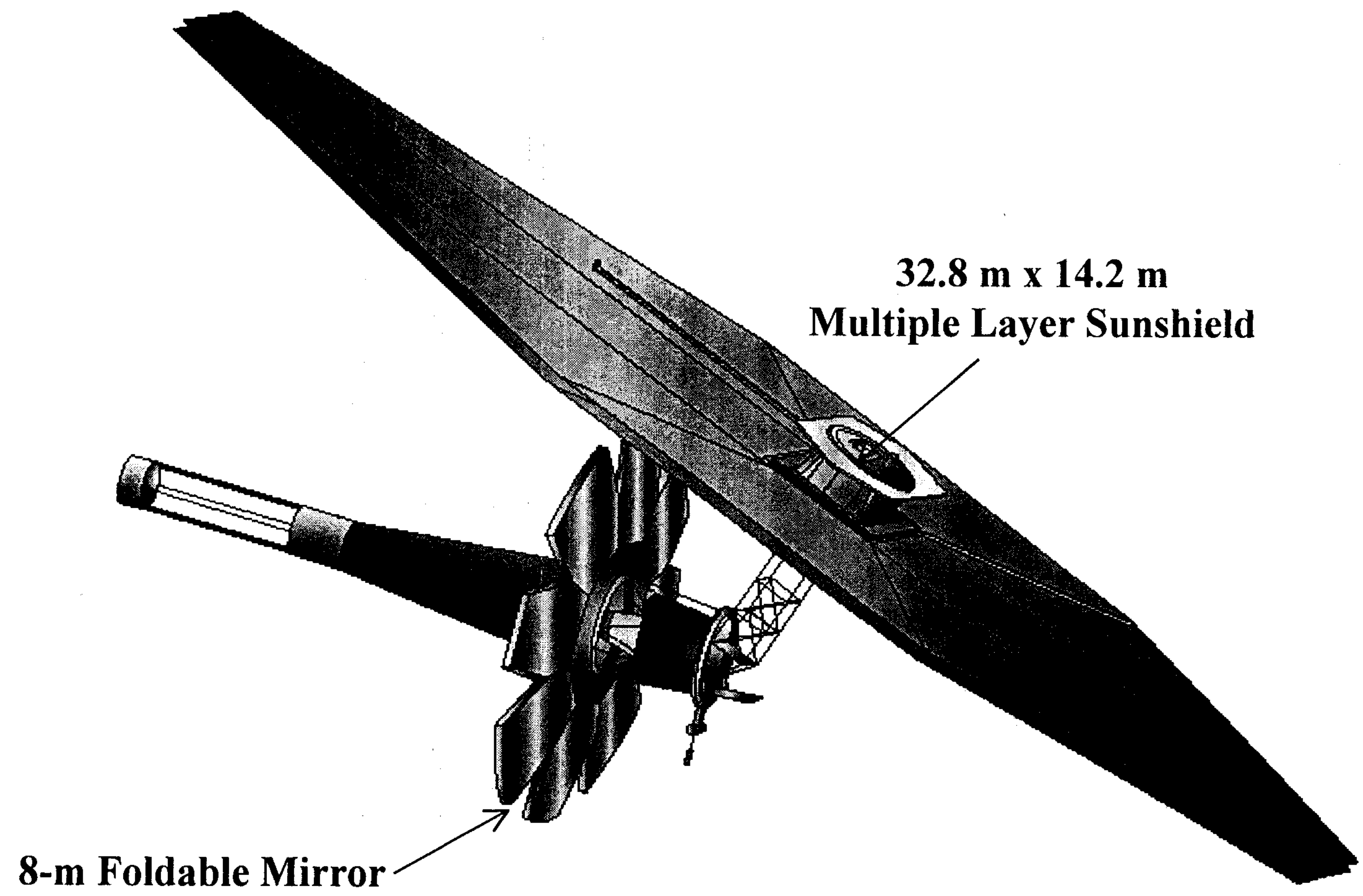
EXAMPLE APPLICATIONS

1) Inflatable Sunshield for the Next Generation Space Telescope (NGST)

2) Inflatable Synthetic-Aperture Radar (SAR) Array Antenna

NGST INFLATABLE SUNSHIELD

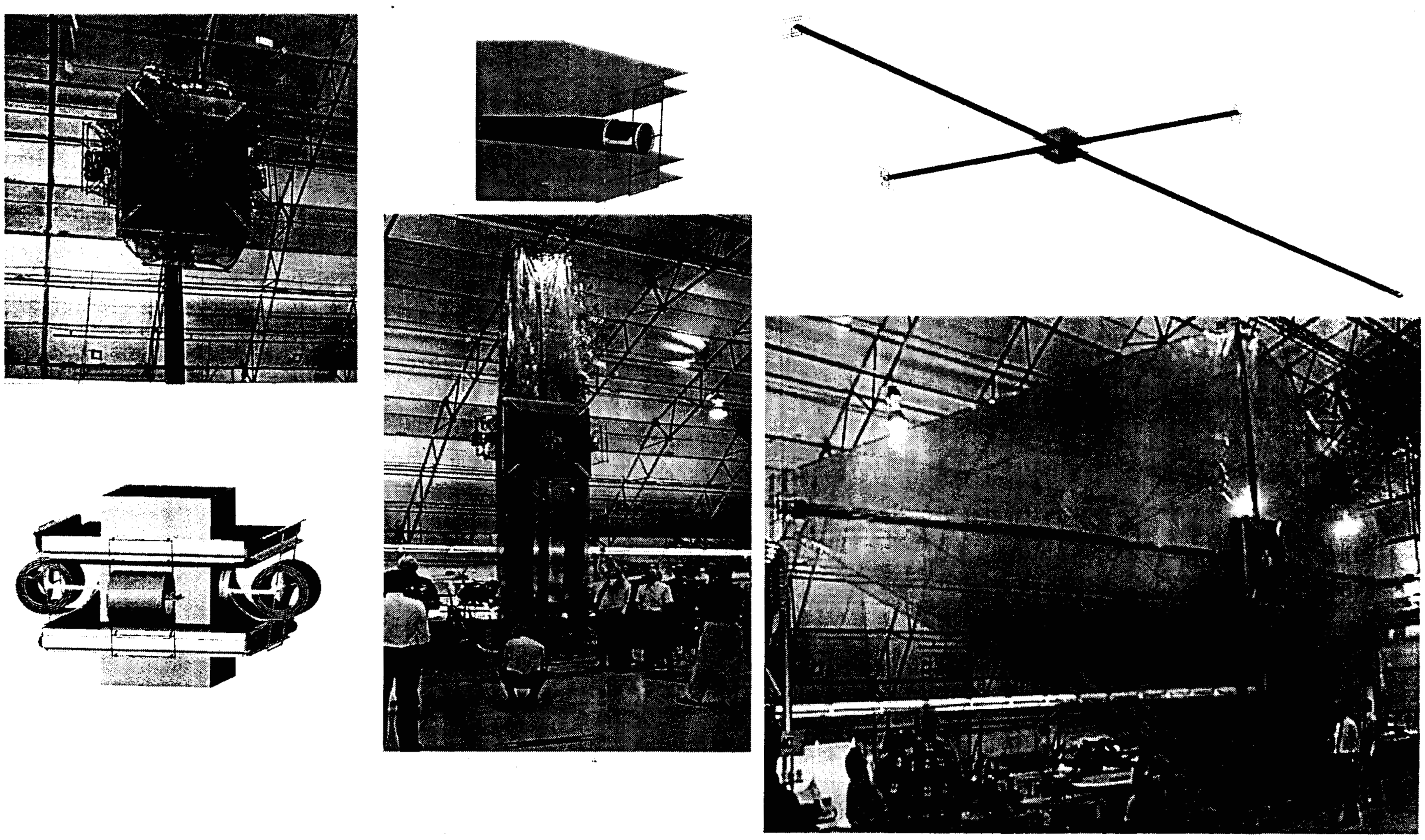
- Next Generation Space Telescope (NGST) is being developed as a replacement of the Hubble Space Telescope.
- NGST requires a 32.8 m x 14.2 m sunshield to passively cool the near-IR telescope to an operating temperature of < 60 K.
- Requirements of NGST sunshield include:
  - Ultra lightweight
  - High packaging efficiency
  - High deployment reliability
  - 5 -10 years of mission life at L2
- A sunshield consisting of inflatable structures and multiple layers of thin thermal films is considered.



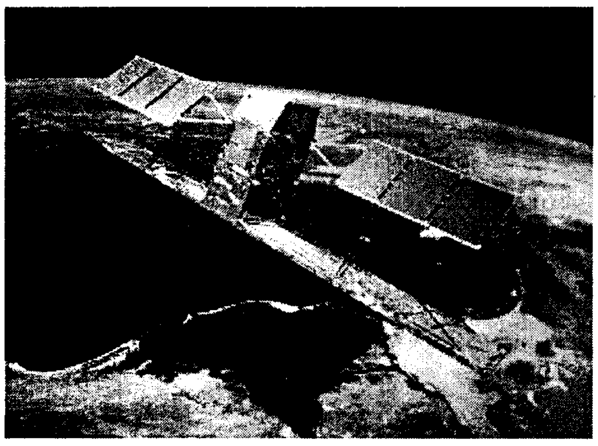
The NGST Reference Architecture

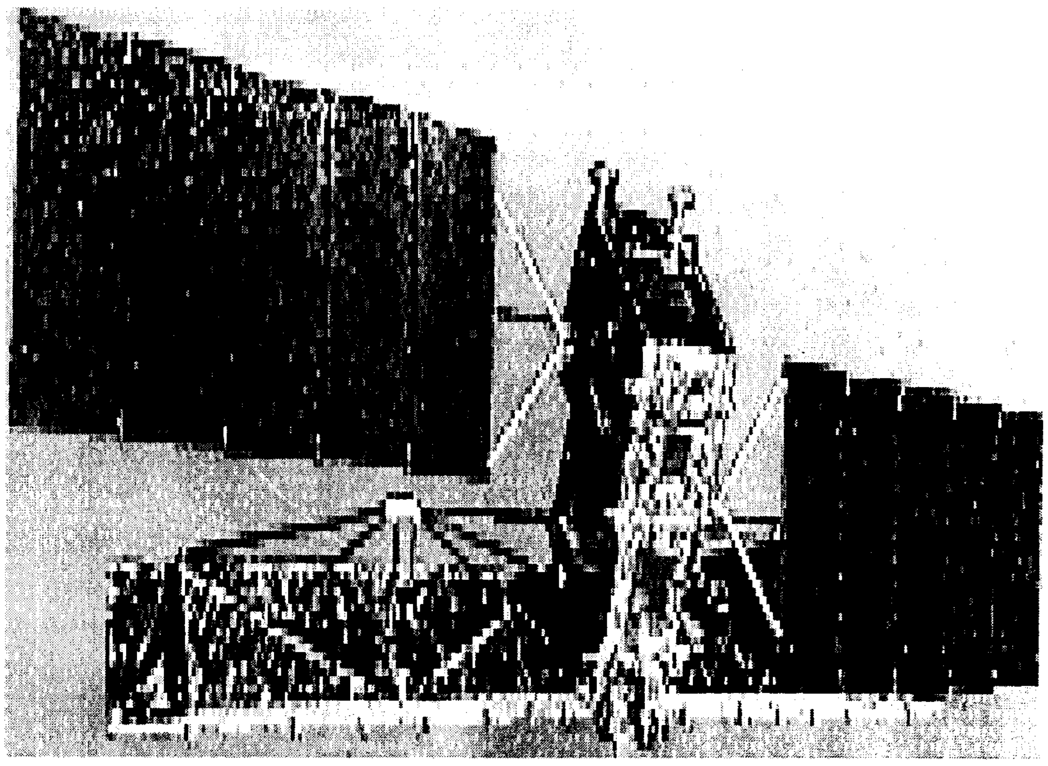
NGST INFLATABLE SUNSHIELD (Cont'd)

- An inflatable NGST sunshield has many advantages over its mechanically deployed counterpart:
  - 20 - 30% lighter
  - 60 - 80% smaller launch volume
  - Cheaper - $5^-M vs. $10^+M
- A major concern is controllability of inflation deployment.
- A 1/2-scale engineering model was developed in 1998 to test-verify controlled deployment and rigidization.
- NASA was working on an space experiment (called the Inflatable Sunshield In Space or ISIS) in 1999 and 2000. However, this effort was terminated last year due mainly to lack of Shuttle flight opportunity.



NGST Inflatable Sunshield EM Deployment Test





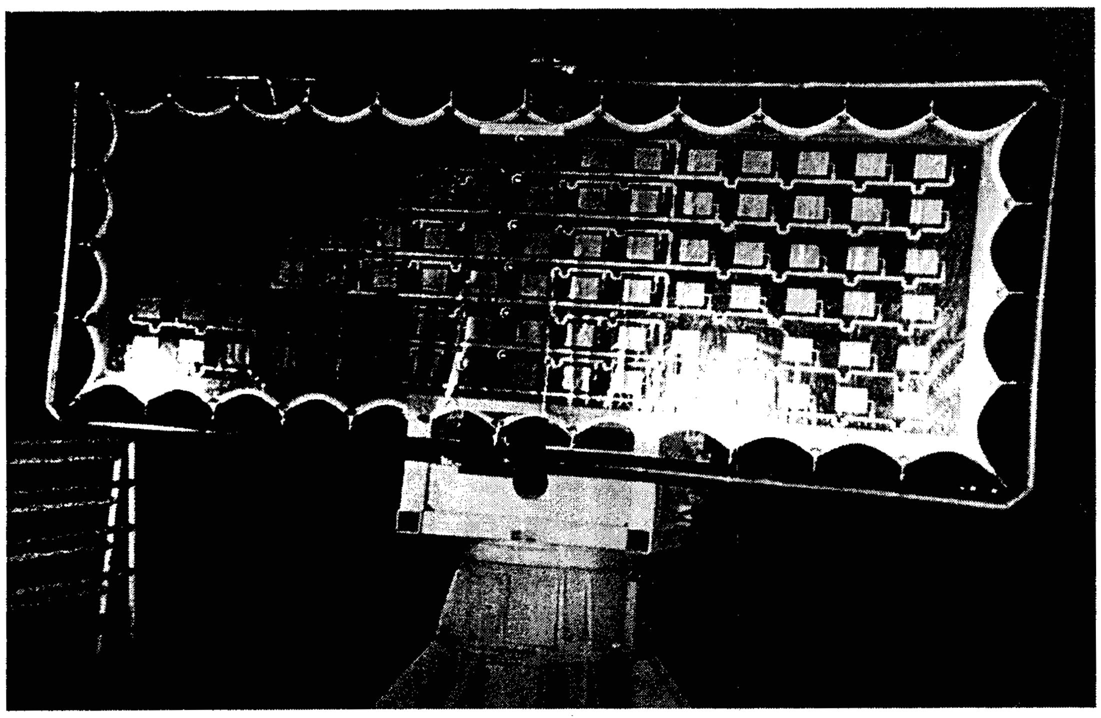
SAR Antenna of Traditional (Rigid-Panel) Design

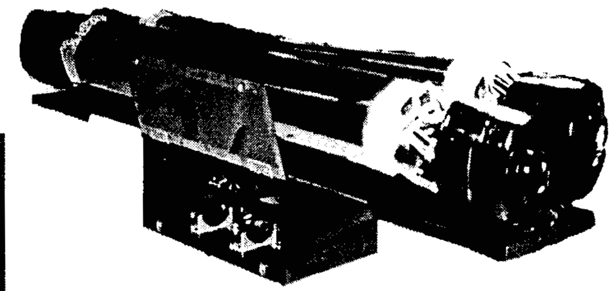
INFLATABLE SAR

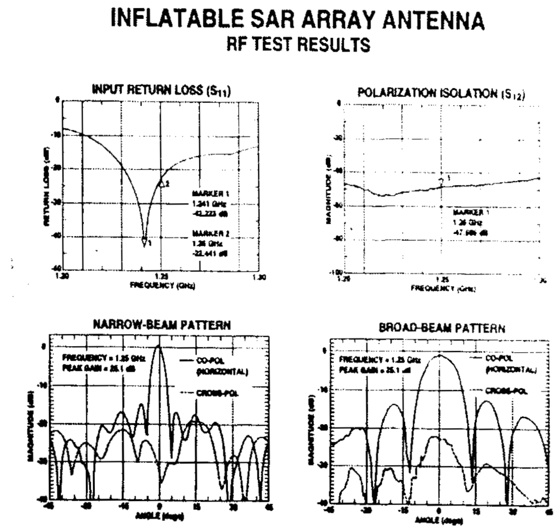
- More synthetic-aperture radar (SAR) missions are needed to assess resources and monitor changes of the Earth - rigid antennas are too big and too heavy.
- JPL was tasked by NASA in 1996 to develop an advanced ultra-lightweight SAR array antenna with RF requirements:
  - 10 m x 3 m aperture
  - L-Band (1.25 GHz operating frequency)
  - Dual polarization and 80 MHz bandwidth
- Radar array is formed by three thin-film membrane layers:
  - Top layer is the radiating plane
  - Middle layer is the ground plane
  - Bottom layer is the micro-strip transmission line plane.

INFLATABLE SAR (Cont'd)

- Mechanical Requirements:
  - Lightweight (less than 3 kg/m^2 of system mass
  - Small launch volume (targeted for launch by Taurus or Athena)
  - Flatness of tensioned membrane layers to be 1 cm RMS
  - Separations to be 1.27 cm between the top two layers and 0.63 cm between the bottom two layers (both with $\pm$ 10% tolerances).
- Two RF-functional 1/3-scale EMs were built and tested.
  - EM by ILC-Dover: Urethane-coated Kevlar booms
  - EM by L'Garde: Stretched aluminum laminate booms
- As a precursor to the inflatable SAR flight experiment (ISAR), a full-scale, single-wing engineering model is being developed at JPL for mechanical testing.







RF Test of An Inflatable SAR (ISAR) EM

Long-Range

Technology Development Roadmaps

Large Lightweight Space Structures

Space Inflatable/Rigidizable Structures

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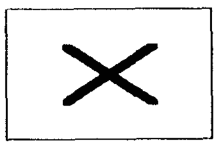
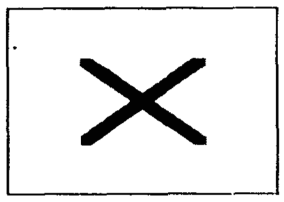


Inflatable Structures

- Tubular structural elements
- Inflation deployment control
- Specialized design and analysis tools
- Materials selection and characterization
- Experimental rigidization technologies
- Scaling laws and ground test methodologies

Enables ground tests, space demos, and technology validation in space

- Inflatable SAR Demo.
- Inflatable Reflectarrays
- ISIS , ISAE, etc.

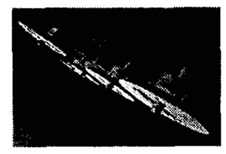


Space Rigidization & Survivability

- Long-term (> 3years) space survivability
- Space-validated rigidization methods
- Space-durable structural materials and thin-films
- Lightweight, compact inflation systems
- Hi-precision fabrication and assembly
- Space-validated design, analysis and performance simulation capabilities

Enables planar inflatable structures* of up to 100 m and reflectors with D/ε ratios of up to 10^5**

- GeoStorm Warning
- NGST, ARISE
- Lightweight, low-cost SAR Missions
- S/A for ESS Missions

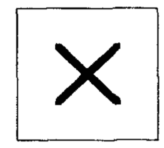


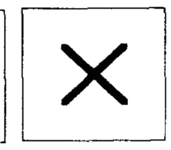
Hi-Precision Structures for Extreme Space Environments

- Survivability in extreme space environments
- Ultra-hi-precision (sub-μm) fabrication and assembly
- Advanced space rigidization concepts
- Adaptive structures and thin-film optics
- In-orbit configuration correction and pointing adjustment

Enables large space optics & reflectors with D/ε ratios of up to 10^7

- TPF
- Large Aperture Observatories
- Exo-Planet Imaging Missions





Space Adaptation & Assembly

- In-orbit configuration change and expansion
- Self-monitoring
- Self-reparability
- Space-based fabrication & assembly

Enables adaptive and expandable space structural systems

- Interstellar Missions
- Evolving Space Colonies

* For examples, solar arrays, sun shades, and solar sails
** D = Aperture diameter; ε = RMS surface error

2001 **2007** **2015** **2025**

M.C.Lou; Jan. 2000

Large Lightweight Space Structures

Large Apertures (Reflectors and Concentrators)

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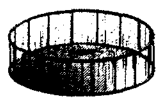


D/ε of up to 10^4

- Support structure: inflatable torus or deployable FRP truss
- Reflective surface: thin-film lenticular or wire mesh dish
- Analysis capability for predicting in-orbit configuration accuracy
- Improvements in fabrication and assembly
- Hi-efficiency packaging concepts

Enables reflectors and concentrators with diameters of up to 20 m and a few mm RMS configuration errors

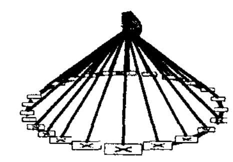
- RF Reflectors
- Technology Validation in Space

D/ε of up to 10^5

- Long-term space survivability
- Space rigidizable torus and support struts
- Thin-film lenticular or hybrid reflective surface (e.g., a thin-film aperture supported by wire mesh)
- Space-durable thin films
- Space-validated design and predictive capabilities
- Hi-precision fabrication, assembly and ground testing

Enables reflectors and concentrators with aperture diameters of up to 40 m and/or sub-mm RMS configuration errors

- ARISE
- Sub-mm Astronomy
- Space Solar Power
- Solar Propulsion

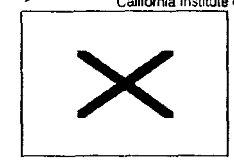


D/ε of up to 10^7

- Actively controlled support structure
- In-space aperture precision adjustment
- Adaptive thin-film optics
- Ultra-hi-precision fabrication and assembly
- Innovative ground test methods and measurements

Enables large apertures with diameters of up to 100 m and/or micro-level RMS configuration errors

- TPF
- IR Telescopes
- Optical Communication
- Earth Science: Event Monitors
- Exo Planet Missions



D/ε ratio of up to 10^9

- Break-through systems concepts
- Breakthrough design, fabrication, assembly and test methodologies

Enables very large apertures with diameters of up to 1,000 m and/or sub-micron RMS configuration errors

- Deep-Field Imaging Observatories

* D/ε is the ratio of aperture diameter divided by RMS surface error

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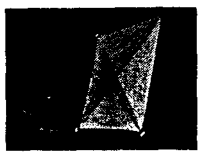
Large Lightweight Space Structures

Solar Sails

Jet Propulsion Laboratory
California Institute of Technology

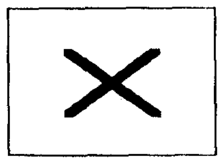


40 to 70 m, 20 g/m²

- Space deployable booms of up to 40 m long (inflatable or FRP)
- Controlled deployment
- Analysis capability for zero-g deployment and performance simulations
- Off-the-shelf or experimental thin films (8 to 16 μm thick)
- Optical reflective coatings
- Hi-efficiency packaging

Enables ground tests and space demo. & technology validation in space

- Solar Sail Space Demo.
- ST-5

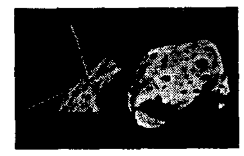


100 m, 10 g/m²

- Space rigidizable booms or radial thin-ribbon ribs
- Spin-deployment and stabilization
- Structure-control interactions
- Space-durable thin-film sails (3 to 5 μm thick) or super-lightweight composite sails
- Scaling laws for ground testing of scaled models

Enables non-Keplerian orbits

- GeoStorm Warning
- Mercury Orbiter



200 m, 3 to 5 g/m²

- Survivability in extreme space environments
- 5 to 10 years mission life
- Spin-deployment and stabilization
- Ultra-thin, ultra-light thin-film (0.5 to 1 μm thick)
- Ultra-thin reflective coatings
- Advanced design and simulation tools
- Advanced fabrication and assembly

Enables long-term low-thrust interplanetary propulsion

- Comet Nucleus Sample Return
- Neptune Orbiter
- Titan Explorer
- Saturn Ring Observer
- Halo Orbit Missions

800 m, 1 g/m²

- Long (> 10 years) mission life
- Innovative system configurations
- Innovative sail concepts
- New structural and sail materials
- In-space fabrication and assembly

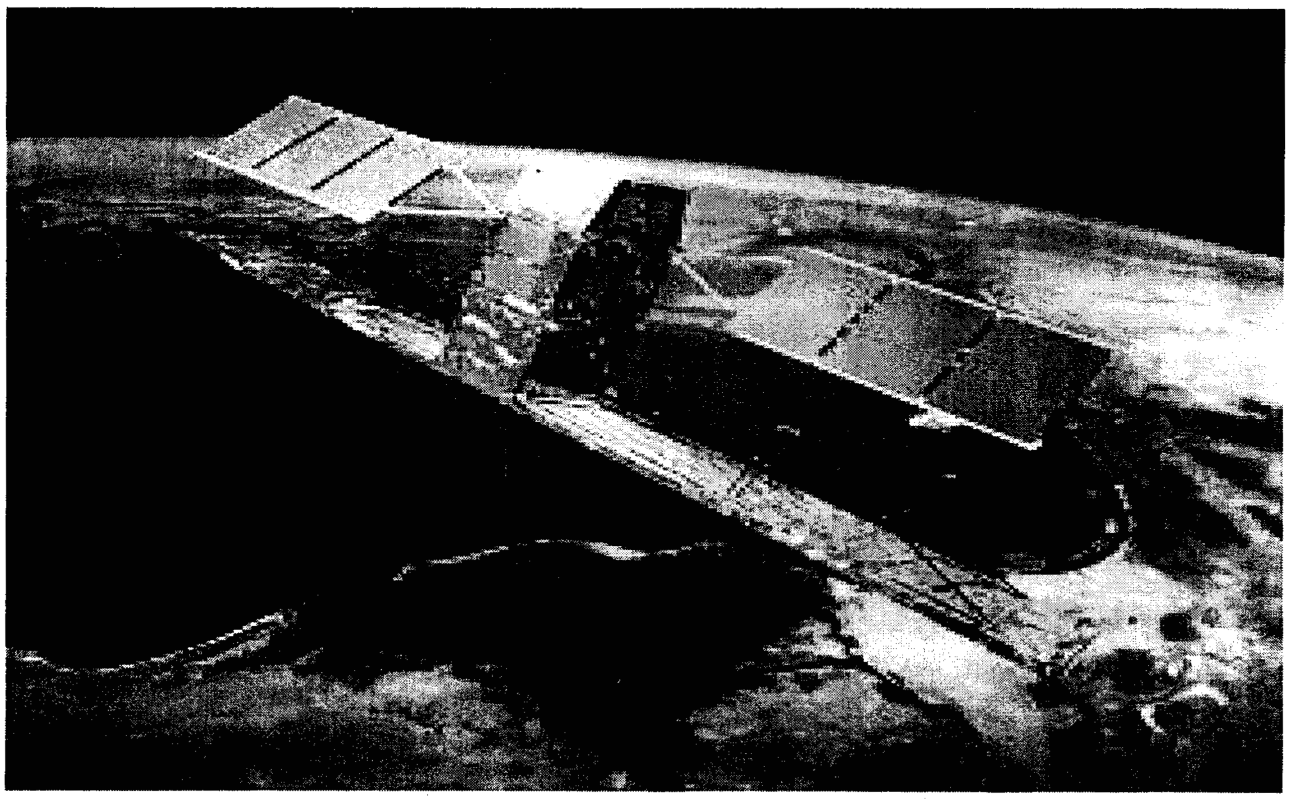
Enables 250 AU space travel in 10 years

- Outer Planet Missions
- Interstellar Missions

2003 | **2005** | **2007** | **2015**

M.C. Lou; Jan. 2000

SPACE INFLATABLE/RIGIDIZABLE STRUCTURES



DEPLOYMENT CONTROL

- Uncontrolled inflation deployment of long flexible tubes can be highly volatile and may damage flight hardware and cause catastrophic mission failures.
- Various inflation deployment control concepts have been developed, including:
  - Sequentially deployed compartments/sections
  - Embedded constant-Force coil springs
  - Velcro Strips
- Stable deployment can be achieved by providing resistive forces to balance the inflation pressure -- this has led to the invention of other advanced control approaches.